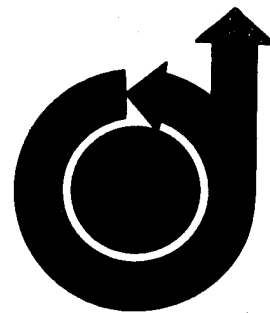


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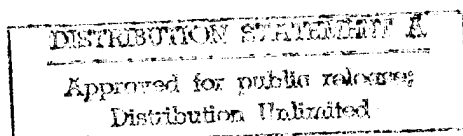
STRUCTURAL APPLICATIONS OF ADVANCED COMPOSITE MATERIALS TO HELICOPTERS

by

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STRUCTURAL APPLICATIONS OF ADVANCED COMPOSITE MATERIALS TO HELICOPTERS

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Abstract

Initial results of a continuing study* have established a technical base for the application of advanced composites to helicopters. A reinforced-composite application analysis relative to two existing helicopters is presented, including the analysis of the rotor and hub systems, drive system, and airframe applications. Initial efforts on the rotor blade have indicated that the anticipated advantages of composites can be achieved. Several rotor blade cross sections are evaluated on a stiffness basis to demonstrate the relative superiority of each design from a minimum weight standpoint. The position of an all-advanced-composite-plastic rotor blade is identified in the parametric field, and the baseline preliminary design blade is established.

Introduction

The Vertol Division of Boeing has a contract with the Air Force Materials Laboratory to develop the required technology and to design and build a set of flight-worthy rotor blades fabricated from advanced composite materials. The program, which started 1 June 1966, will culminate with the fabrication of a 3-blade set on the aft rotor of the Boeing-Vertol CH-47 helicopter (see Figure 1).

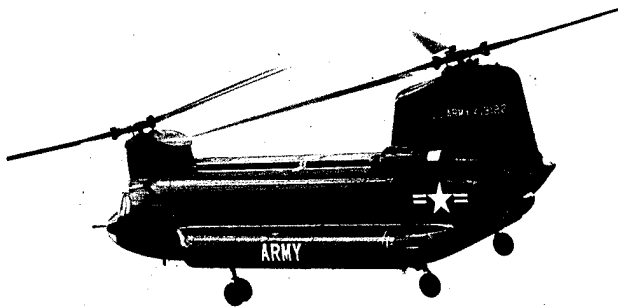


FIGURE 1. BOEING-VERTOL CH-47 HELICOPTER

*The reported work was accomplished under Air Force Contract AF33(615)5275, "Research and Development of Helicopter Rotor Blades Utilizing Advanced Composite Materials," under the direction of the Advanced Filaments and Composite Division, AFML; Captain David S. Dickson, Air Force Project Officer.

While the ultimate hardware will be a set of rotor blades composed of a high percentage of boron fibers, the initial portion of the program, as shown in Figure 2, included studies of a broader scope. Some of the results of these early program studies in design optimization, analysis techniques, design properties, applications analysis, and preliminary design are presented here. The brevity of this paper limits us to a summary of the more significant findings. Complete details of the work and the results can be found in References 1, 2, and 3.

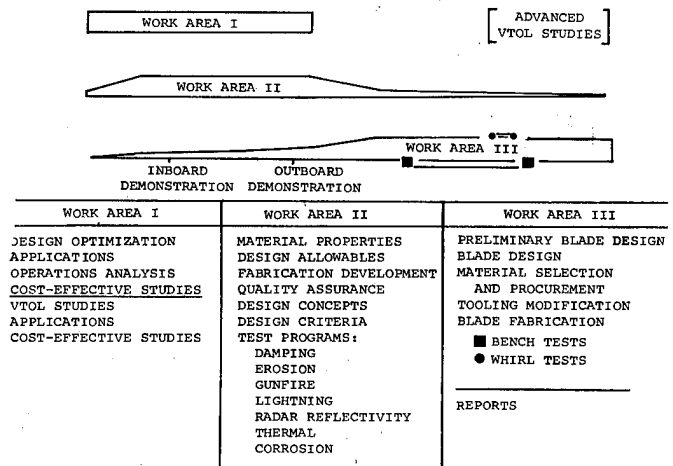


FIGURE 2. PROGRAM TO DEVELOP TECHNOLOGY FOR RELIABLE ADVANCED FIBROUS REINFORCED COMPOSITE ROTOR BLADES

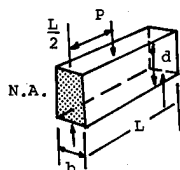
This program presents a unique challenge to the structural analyst and designer. The advanced composite material rotor blades must have the high reliability and structural integrity associated with structures of more conventional materials. In the past, this high reliability in composite materials has been achieved by designing as if they were special types of homogeneous quasimetallic materials, and then by applying generous factors to compensate for the inaccuracies of this assumption. However, the primary objective of this program is to demonstrate through fabrication and test the attainment of the high potential for composites. This can be accomplished only by recognizing them as a new class of materials and by developing analytical techniques and properties in accordance with their unique characteristics.

Analytical Method

A wide variety of properties is obtainable from composites by varying the fibers, the matrix, the fiber orientation, and the volume percentage of fibers. The objective of the design optimization study was to define methods for achieving the optimum combination of properties for a given application. The basic approach that was developed is the classical optimization procedure; this is demonstrated in Figure 3 for a solid rectan-

gular beam. The first step is to define the optimization goal; in this case, to minimize weight while meeting a maximum deflection criterion. The function of the element, the constraints, the fixed parameters, the variables, the assumptions, and the relationships between the variables are then established. For this example, only unidirectional fibers (i.e., fibers oriented with the load) and uniform fiber distribution are considered. Obviously, other examples can be evaluated in a similar manner.

The relationships are then combined in a way that expresses the item to be minimized (i.e., weight) as a function of the principal variable (i.e., modulus of elasticity). This is the important point with respect to composites: with a fixed criterion, weight can be minimized by obtaining the optimum fiber-matrix combination. The relationship developed is between weight, the fixed deflection criteria, the beam dimensions, the effective modulus of elasticity of the composite, and the



ELEMENT: SIMPLY LOADED RECTANGULAR BEAM

FUNCTION: BEAM A CONCENTRATED LOAD TO END SUPPORTS

OPTIMIZATION GOAL: MINIMIZE WEIGHT WHILE MEETING A MAXIMUM DEFLECTION CRITERION

CONSTRAINTS: FIXED LOAD AND SPAN, BEAM WIDTH FIXED BY ATTACHMENT REQUIREMENTS

FIBER ORIENTATION: UNIDIRECTIONAL FIBERS ORIENTED PARALLEL TO THE BENDING STRESSES

Variables

v_f	fiber volume fraction
$1-v_f$	matrix volume fraction
E_T	modulus of elasticity - tension side
$E_{T_{max}}$	modulus of elasticity at outer beam fiber
E_C	modulus of elasticity - compression side
ρ_m	density of the matrix
ρ_f	density of the fiber
ρ_c	density of the composite
E_m	modulus of elasticity of matrix
E_f	modulus of elasticity of the fiber
E_{eff}	effective modulus of elasticity of the composite
E_{opt}	effective modulus of elasticity of the composite which results in minimum weight
b	width of the beam
d	depth of the beam

properties of the constituents. Since for a given material system the properties of the constituents are fixed, all the factors in this example are known except weight and the effective modulus of elasticity. Thus, by differentiating weight with respect to the effective modulus of elasticity and equating to zero, the equation can be solved to find the value of E_{eff} (effective modulus of elasticity of the composite) which gives either a maximum or minimum point in the weight-modulus relationship. Testing demonstrates that the solution shown is for a minimum. Thus, an effective modulus is defined which gives the minimum weight for a solid rectangular beam of fixed width. It should be noted that the optimum modulus is defined in terms of properties of the constituents only, and that it is valid for the beam described regardless of load, deflection requirements, or dimensions. This information can be used in a variety of ways; typical relationships for uniform fiber distribution through the beam are shown in Figure 3. Here the

Relationships for Uniform Fiber Distribution Through the Beam

$$\left. \begin{aligned} E_{eff} &= v_f E_f + (1 - v_f) E_m \\ \rho_c &= v_f \rho_f + (1 - v_f) \rho_m \end{aligned} \right\} \text{Rules of Mixture} \quad (1)$$

and

$$\rho_c = \left(\frac{\rho_f - \rho_m}{E_f - E_m} \right) (E_{eff} - E_m) + \rho_m \quad (2)$$

$$\delta = \frac{PL^3}{48E_{eff}I} \quad (3)$$

or

$$d^3 = \frac{PL^3}{4\delta} \times \frac{1}{bE_{eff}} \quad (4)$$

Deflection Formula

Sample Derivation

From the previous relationship, an expression for the minimum weight composite modulus is developed for a solid rectangular beam with uniform fiber distribution in the following manner:

Weight per inch of length, W/in.,

$$W/in. = \rho_c A = \rho_c b d. \quad (5)$$

Substituting equation (3) for " ρ_c " gives:

$$W/in. = \left(\frac{\rho_f - \rho_m}{E_f - E_m} \right) (E_{eff} - E_m) b d + \rho_m b d. \quad (6)$$

Substituting equation (5) for "d" gives:

$$W/in. = \left[\left(\frac{\rho_f - \rho_m}{E_f - E_m} \right) (E_{eff} - E_m) b + \rho_m b \right] \times \sqrt[3]{\frac{PL^3}{4\delta} \frac{1}{bE_{eff}}} \quad (7)$$

Then, differentiating W/in. with respect to E_{eff} , and setting $dW/dE_{eff} = 0$ gives

$$0 = E_{eff} \left[\frac{\rho_f - \rho_m}{E_f - E_m} \right] - \frac{1}{3} \left[\left(\frac{\rho_f - \rho_m}{E_f - E_m} \right) (E_{eff} - E_m) + \rho_m \right]. \quad (8)$$

Solving for E_{eff} gives the E_{eff} for minimum weight,

$$E_{eff} \left(\frac{dW/dE_{eff}}{dE_{eff}} = 0 \right); E_{opt} = \frac{\rho_m}{2} \left(\frac{E_f - E_m}{\rho_f - \rho_m} \right) - \frac{E_m}{2}. \quad (9)$$

FIGURE 3. TYPICAL ORGANIZATION PROCEDURE FOR ELEMENTS FABRICATED FROM ORIENTED FIBROUS COMPOSITES

optimum fiber volume is shown as a function of the ratios of the modulus of elasticity of the constituents (i.e., fiber and matrix) and the ratios of their densities. Figure 4 gives the optimum fiber volume fraction for any material system. The above technique can be applied for stress-critical structures, frequency-critical structures, and for simple or complex elements. Studies have been completed for a variety of standard elements, i.e., hollow and solid rectangular, circular, and elliptical beams; and for the load conditions of interest, bending, shear, and torsion.

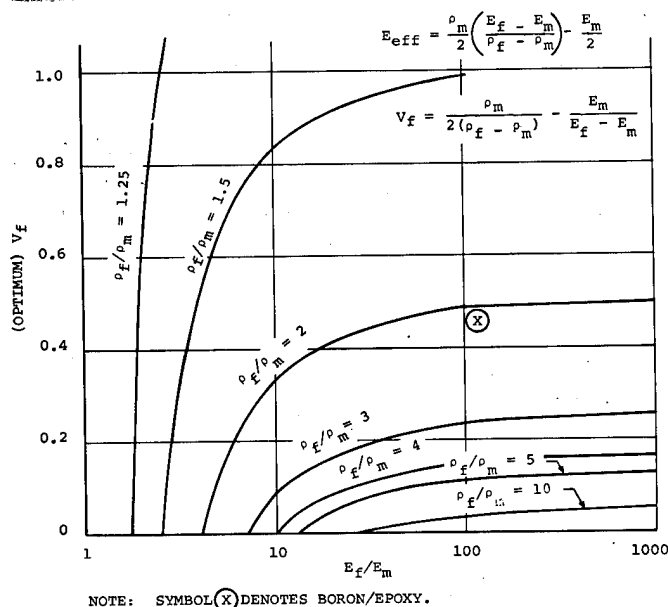


FIGURE 4. OPTIMUM FIBER VOLUME FOR RECTANGULAR SOLID BEAM OF KNOWN WIDTH WITH UNIFORM DENSITY UNIAXIAL FIBERS WHEN BEAM IS CRITICAL IN BENDING STIFFNESS

The weight equation can also be used directly to trade dimensions, deflection limits, and composite property relations to obtain minimum weight. This is facilitated by the use of nomographs as shown schematically in Figure 5. Four graphs are arranged so that horizontal and vertical projections between graphs will directly relate criteria, dimensions, and material properties to weight per linear inch. The example shown is taken for the developed relationships for a hollow rectangular or circular beam. The first graph in the top left corner of the figure represents lines of constant deflection criteria as a function of the beam effective modulus of elasticity and moment of inertia.

The next two graphs are developed relationships between dimension ratios which determine the stiffness characteristics (S.F.) and the area (A.F.) of the beam. The development of these graphs is described in detail in Reference 3. The stiffness factor and the area factor are readily developed in terms of the wall thickness-to-depth and beam-to-depth ratios and that they are presented graphically in Reference 3. The final graph is simply the relationship of beam weight as a function of composite density and cross-sectional area. Scales for all four graphs are logarithmic.

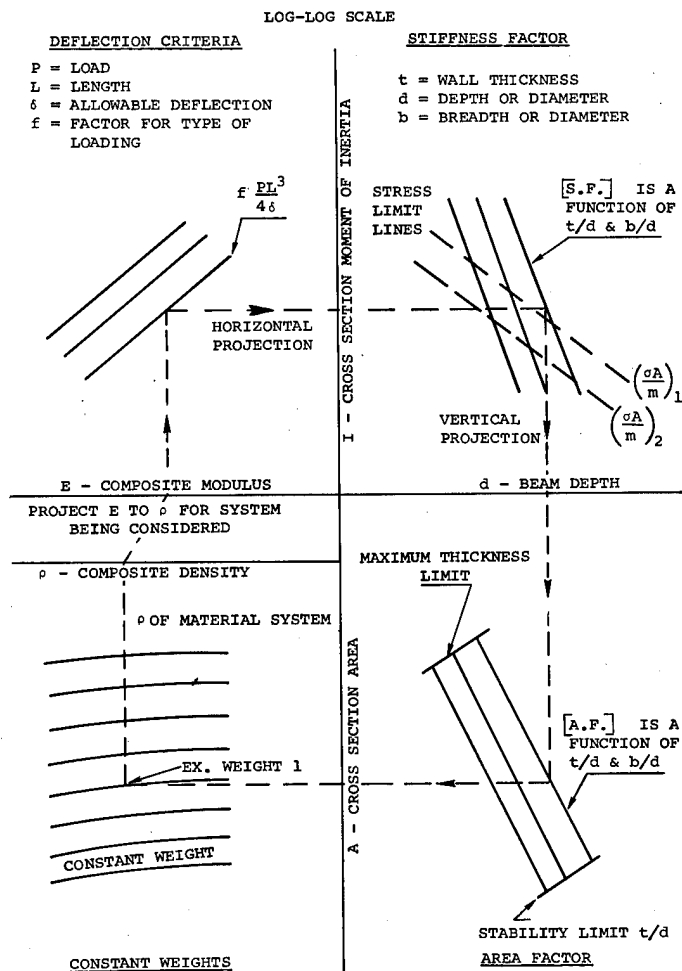


FIGURE 5. WEIGHT TRADE NOMOGRAPH FOR HOLLOW RECTANGULAR OR CIRCULAR BEAM

Using this nomograph it is possible to trade the effects of all pertinent parameters on weight. This presentation is not limited to a single material or material system; it is necessary only to use the density that corresponds to the modulus of elasticity for the material system being evaluated. Information on the relationship between modulus and density for various material systems is available from literature or is readily developed from micromechanics. The example shown is for a stiffness-critical structure; however, it can easily be modified to include stress or natural-frequency criteria. For example, stress is related to the moment and beam dimensions by $\sigma = MC/I$, or $\sigma/M = C/I$. Lines of constant allowable stress/moment are easily plotted as shown on the second graph.

It is worthy of mention in connection with advanced composites (i.e., boron and graphite) that, while stress must be checked, optimization should be concentrated on modulus-dependent performance parameters. The strength-to-weight characteristics of advanced composites are only moderately better than those of existing glass composites, whereas their modulus-to-density relationships are many times better. Therefore, while the cost for these materials remains high, they will provide cost-effective results only when their stiffness can be used effectively.

Anisotropic Material

Composite materials in their most effective forms, i.e., highly oriented fibers, are highly anisotropic. The effective use of these materials requires that any analysis consider this anisotropy. Stress analysis of complex structures at Vertol Division is accomplished by computerized methods using a direct-stiffness approach. Briefly, this procedure is to idealize the structure by dividing it into discrete node points, and then to connect these node points with structural elements which provide the response of the real structure. Obviously the adequacy of the solution is directly dependent upon the validity of the elements and the nodal distribution.

Rectangular orthotropic elements have been developed by Vertol Division to account for the anisotropy of the composite material. Rectangular elements were selected since the geometry of a rotor blade allows a rectangular gridwork for the nodes over most of the blade; the use of these orthotropic elements has provided satisfactory results for most of the blade area. However, near the root end where the blade tapers, the use of rectangular orthotropic elements necessitates extensive studies and modifications to achieve adequate results. Thus, while the orthotropic elements have been used for this contract, it can be stated that the most efficient analysis of composite materials requires triangular anisotropic elements. Such elements are currently being developed at Vertol Division.

Due to the complexity of the rotor blade cross section design, a number of idealization studies were required to establish the exact idealization desired. The objective of these studies was to define the best compromise between the accuracy of a very detailed nodal gridwork and the efficiency of a very coarse nodal gridwork. The basic cross section of the blade is shown in Figure 6.

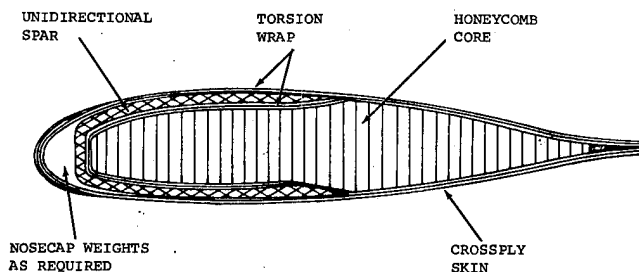
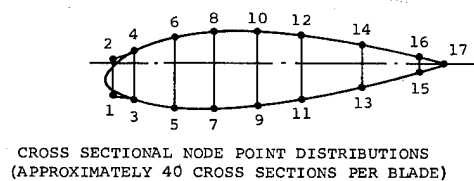


FIGURE 6. TYPICAL CROSS SECTION OF A BORON ROTOR BLADE

The most precise idealization would be one which divided the blade cross section so that a separate element was used for each group of like plies, core, and bond area. The blade would be divided in the chordwise direction so that a transverse row of nodes would exist at each major change in dimension or fiber layup. In the flapwise direction, the spacing would be dictated by changes in geometry, load distribution, and desired fineness in stress distribution. While precise, this idealization would be extremely inefficient and time consuming. The procedure that was used first analyzes the blade using a fine nodal gridwork; sequentially, more coarse idealizations were then made.

This procedure was continued until there was a major deviation in the calculated stresses and deflections. The most coarse and thus the most efficient gridwork, which showed no significant deviation, was selected. The idealization anticipated for use is shown in Figure 7.



BLADE CROSS SECTION BLOWUP

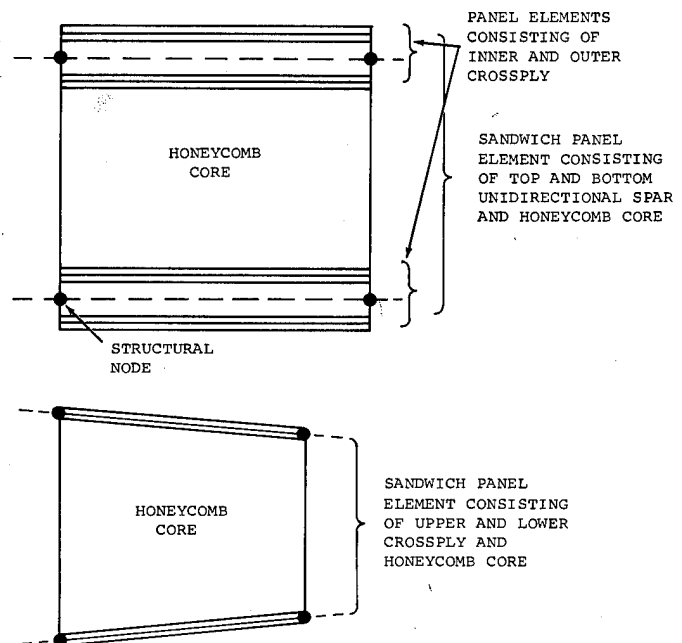


FIGURE 7. STRUCTURAL IDEALIZATION OF COMPOSITE ROTOR BLADES

There is a significant limitation to the gridwork adopted in that it does not give a good picture of the stresses between plies which exist because of strain incompatibilities. It will therefore be necessary to examine critical areas in greater detail, approaching the fine gridwork that was discussed previously. Since the coarse idealization will give good values for the gross forces and deflections between node points, this detailed evaluation can be accomplished in a separate analysis.

Microanalysis

The macroanalysis studies, i.e., studies which consider the composite to be a quasi-homogeneous anisotropic material, have been complemented by microanalysis, i.e., studies which evaluate the material as a microstructure of axial-load-carrying elements (fibers) and shear elements (the matrix). These studies provide significant guidance to the rest of the program. One of the most significant conclusions from these studies is that the efficient use of oriented composites requires that the stresses coincide with the principal fiber directions. This is

demonstrated in Figure 8, in which the relative stress concentration is shown for fibers around the hole. Only a few of the fibers are shown for the sake of clarity. However, the effect is evident: the maximum stress concentration is much lower than the 2.0 to 3.0 that is found when the fibers are cut at the hole. This conclusion is, of course, intuitive and has been reported by General Dynamics and by others. Unfortunately it is too often overlooked in the design of composite structures, resulting in unnecessary, premature failures.

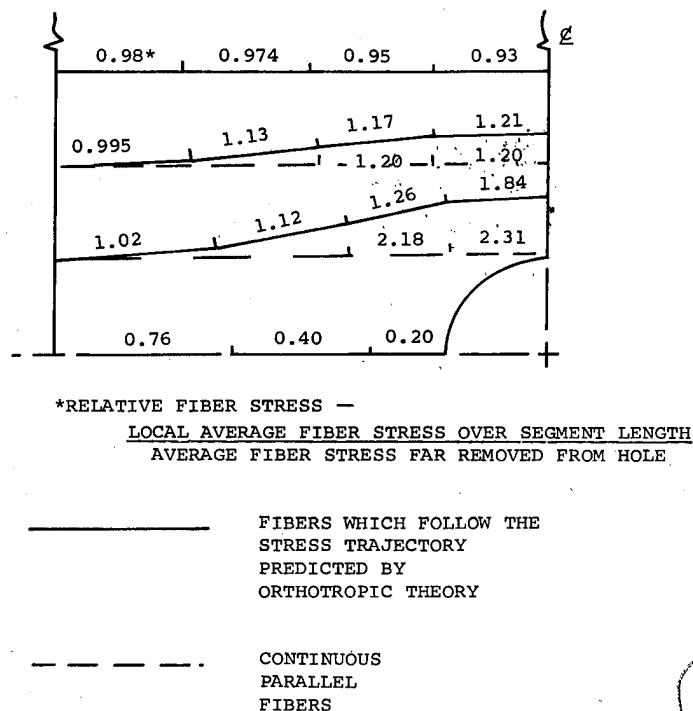


FIGURE 8. RELATIVE STRESSES IN FIBERS IN THE AREA OF A SMALL DISCONTINUITY

Properties Evaluation

The performance and integrity of the final hardware is directly dependent upon the properties of the material and their assurance in the final hardware. Vertol Division is conducting a major program for establishing and understanding the properties of the composites to be used in the final hardware. The program effort on material properties is twofold. The first effort is the projection of properties which can be obtained in the future; these are used to guide various studies on the potential of composites. The concurrent second effort is the determination of the properties of today's materials, since these will be used for hardware and design and analysis. The objective of this property work is to assure the successful demonstration of the advanced composite rotor blade. The following ground rules apply:

- Single source of information
- Base design properties on data
- Provide properties on a timely basis
- Confirm design properties on representative materials
- Maximum use of latest technology
- Best prediction of final properties throughout program
- Plan uncertainties to the conservative side so that changes are positive
- Properties compatible with analysis methods
- Format understandable by users

The basic requirement for the design properties for this program is that they provide the stress analyst with information that will assist him in assuring the structural integrity of the rotor blades. It is of prime importance to the program objective that the properties be representative of the most advanced materials, analysis techniques, and other factors; thereby contributing to their most efficient use. In other words, while the required structural integrity must be achieved, it must also be accomplished with the minimum penalty to the evaluation of the composite structure.

The design properties must be available on a timely basis. Three key points in the program have been identified with respect to properties availability: preliminary design, design of demonstration hardware, and design of final hardware. Accordingly, an initial release of the best information available was made early in the program, with continual upgrading as more information has been developed. The goal is to have the least possible property change throughout the program. It is recognized, however, that changes are inevitable as the technology grows. Even moderate reductions of properties late in the program might result in underdesigned parts requiring costly and time-consuming redesign. Conversely, moderate increases in properties might produce designs with structural efficiencies lower than desired. No redesign would be required, however, and a more optimized design for composites could be projected based on these improved properties. Therefore, while preliminary properties will be the best estimate of final values, the tendency is to be pessimistic about projected or unsubstantiated improvements.

In order to insure uniformity throughout the program, a structural properties document has been produced and is maintained as the only source of design information. This document is issued on a controlled basis to the cognizant design and analysis personnel.

The design properties must be compatible with the analysis techniques used and they must be presented in a comprehensible form. Both the analysis techniques and the comprehension of the users are changing throughout the program; therefore, the manner of data presentation is also changing. Initial releases have been made on a basis of net area properties. The limitations of properties presented on a net area basis are recognized, as are the potential advantages of presenting properties on a more fundamental basis. However, it is the feeling at Vertol Division that the validity of these more refined methods in practical applications has yet to be proven. Nevertheless, the properties are presented in a direct, practical manner which provides for microanalytical considerations, anisotropic behavior, and variations in material geometries and load directions.

Test Techniques

The properties must represent the performance of the material in the actual component, under the load and in the environment anticipated in service. The test data required for the establishment of design properties necessitates test techniques representative of the service load and material reactions, or the ability to correlate coupon results with component performance. Analysis and materials technology can provide important insight into material behavior and can establish

trends and considerations. However, experience has shown that the variables are too numerous to allow the direct theoretical quantitative prediction of the performance of even simple metals without test verification. Therefore, design properties will be based on representative test data. Theory, both micro-analytical and macroanalytical, is used for extrapolation, interpolation, and establishment of trends.

Fatigue properties of the composites have been of particular concern. In metals, when design properties are established from coupon data, they are reduced for component performance on the basis of empirical factors developed through many years of experience. In general, there is no comparable experience for the composites, particularly the advanced composites. A great deal of attention is being focused upon coupon-component correlation, especially for fatigue.

Limited data has indicated that for composites the reduction required between coupon and component may be much less than for metals. However, until this is established through extensive correlation, it will be necessary to use arbitrary reduction factors while recognizing that this may penalize the composites. The approach that is currently being followed at Vertol Division is demonstrated in Figure 9. The results of tension-tension tests on unidirectional boron-epoxy composites loaded parallel to the fibers at a stress ratio of 0.1 can be seen on this plot. The design number is obtained by determining the statistical minimum for the coupon data at 10^7 cycles, reducing this statistical minimum by an arbitrary factor of 1.75 at 10^7 , and then projecting back to 10^5 cycles, using the best fit line to the data. From 10^5 cycles, the design curve is projected back to the static limit strength of the material. It should be emphasized that this design curve does not necessarily represent what can be achieved in boron composites; rather, it is a curve which is intended to assure structural integrity. Certainly, the curve is influenced by the relative ignorance of the performance of components.

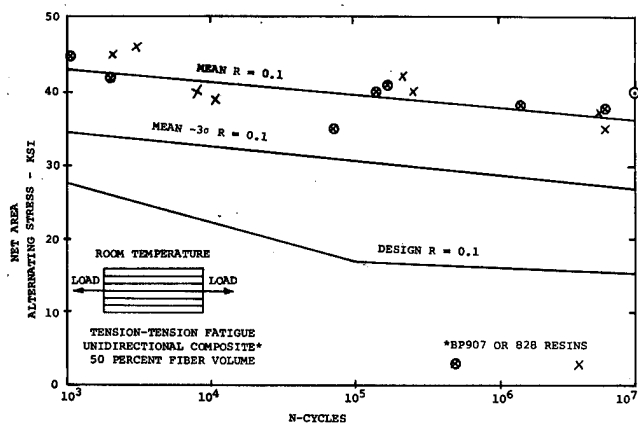


FIGURE 9. TYPICAL DESIGN S-N CURVES FOR UNIDIRECTIONAL BORON COMPOSITES

The work discussed in the previous sections has been directed primarily toward the establishment of a technical base for applying composites to helicopters. Application studies have been accomplished which extend beyond the rotor blade to the entire aircraft.

Application Studies

The basic philosophy of the applications analysis was to conduct a design and technical study unencumbered by manufacturing and material cost considerations, free to take advantage of any improvement offered by boron composite material properties. The applications study proceeded concurrently with design optimization studies; a dynamic exchange of data and requirements created continuity between the two efforts. The operations and economic studies will stem from the results of the applications analysis; therefore, to close the loop between design, technology, and operations studies, the groups which normally support them were included in the structure of the application study. Their guidance and suggestions were sought in determining which components were to be considered in addition to those selected by the design department. The operations analysis model will be based on dependability, capability, and availability; and the economic study will consider the cost of the product and the cost of ownership.

The helicopter applications study was divided into four parts: the rotor group, the drive system, the airframe, and the rotor blade. The rotor group consisted of the rotor hub and the upper flight controls; the drive system was subdivided into the transmissions and the drive shafting. The rotor blade was placed in a separate category since it entailed a study that was significantly larger in scope than that of the other components.

The rotor group study is essentially the study of the dynamically loaded components. In general, the components within this group are designed to a fatigue criterion and the resulting hardware items are relatively heavy in comparison to their normal loads. As a result of their poor load-weight efficiency they account for a large proportion of the helicopter empty weight; therefore, they are obvious targets for low-density advanced reinforced composite application. The rotor group, shown in Figure 10, comprises those items between the vertical pin and the hub. The dynamic controls that were studied were essentially the upper controls, consisting of the pitch-links, rotating and non-rotating swashplates, and drive scissors (also shown in Figure 10). Attempts to design pitch shafts and pitch housings were unsuccessful; consequently, it was concluded that dynamic structures which have a series of short coupled joints or rapid load-path changes do not lend themselves to composite applications. The critical boron material consideration in this case is the minimum bend radius limitation imposed by the fiber modulus of elasticity and the associated material strength degradation associated with the bend radii. The rotor hub, however, was identified as a potential composite application which would result in a 24-percent weight saving. The weight saving is modest because the anticipated low point-load bearing strength for composites necessitates the use of metal inserts, and this reduces the expected weight savings. The application payoff may include both a weight saving and an improved manufacturing cost record. Critical phases of the hub machining require close tolerance control of shaft spline and hinge pin alignment. Even moderate errors in alignment in either operation can result in scrapping the entire expensive component. However, with a filament-wound hub incorporating a metal splined center spool and premachined hinge pin inserts, the machining time required to make all these components would not be lost, if, in final assembly, one of the surfaces was damaged.

Rotor Hub ~ 24% wt saving
w/ Boron Fibers

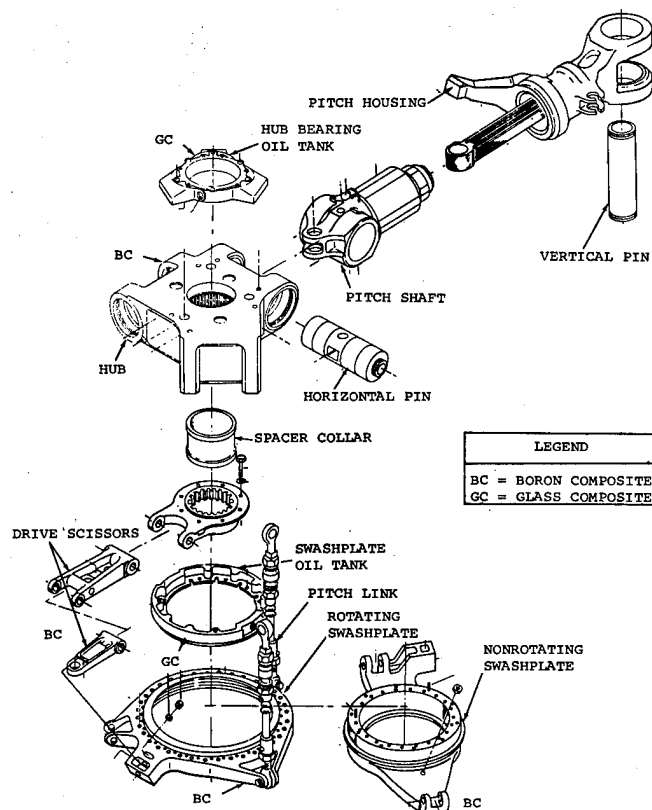


FIGURE 10. MAJOR COMPONENTS OF CH-47 HUB AND UPPER CONTROLS

A torsional improvement in the rotating swashplate ring (shown in Figure 10) in the direction of increasing stiffness will reduce the rolling or twisting of the bearing races and will thus improve the ball bearing orbital path. The anticipated payoff for this high-modulus composite application to the swashplate system is an improvement in the life of the bearing that connects the rotating and nonrotating swashplates. This application of composites also improves design control of the stiffness in the pitch-change reaction load path. On the basis of a similar consideration the swashplate drive scissors may also be optimized on a stiffness-versus-deflection basis.

The epoxy and chopped-glass material was identified as having a payoff for the various oil tank and reservoir components in the dynamic system. This material would provide a one-for-one replacement for magnesium, on the basis of modulus-of-elasticity data from the literature. The components would be about 6 percent heavier due to the increased density. It is anticipated that for this modest weight penalty the corrosion problem associated with magnesium could be avoided; in addition, the components could be injection-molded using fluid plastic slurries of chopped glass, with reduced fabrication costs.

The essential elements of the drive system study are shown in Figure 11. A failsafe application was attempted using composites in the internal cores of the forward and aft rotor shafts. It was estimated that a composite core could support the fully fractured rotor shaft for a short period of time. While the theoretical calculations did not indicate that a failsafe structure was achieved, the results were sufficiently encouraging to warrant further development evaluation.

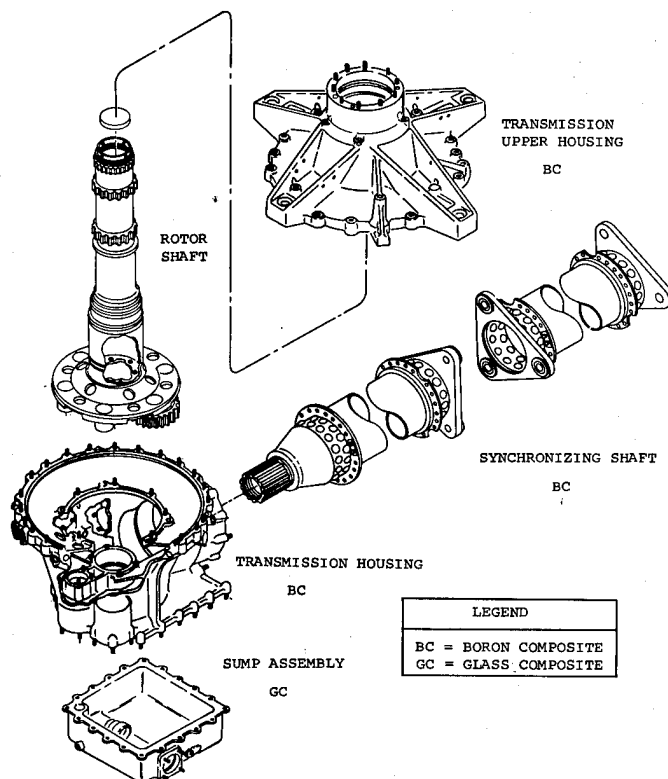


FIGURE 11. MAJOR COMPONENTS OF CH-47 FORWARD ROTOR DRIVE SYSTEM

The transmission cases were shown to be very desirable applications of boron composites, providing an ideal structural component to benefit from the great stiffness of the material. The improved stiffness is expected to provide increased transmission life by reducing the variation in gear tooth wear and fatigue loading caused by power level changes through the gear system. It is also anticipated that the life of the gearshaft support bearings will improve as the shaft end slopes decrease with increasing box stiffness.

Design Studies

A detailed design study was executed and is shown in Figure 12 for the replacement of a transmission aluminum upper gearcase with composites. This study revealed that the mechanical attachment and the frictionless bearing seat problems could not be avoided conveniently and required steel reinforcements, which reduced the overall weight saving that was expected. Where magnesium transmission cases are currently in use, boron composite replacement results in only a moderate weight saving. This reflects the weight penalties associated with installing metal inserts and bearing seats, as well as the initial low density of magnesium. The anticipated weight saving is 30 percent for aluminum boxes and 18 percent for magnesium boxes. In those cases where magnesium is the basic material it is anticipated that composites will obviate the corrosion considerations.

The objective of the composite application on light-gage torsional drive shafting is to take advantage of the potential increase in bending stiffness and to decrease weight. The product of these features is a lighter, longer shaft which can be manufactured by filament winding. The increased length elimi-

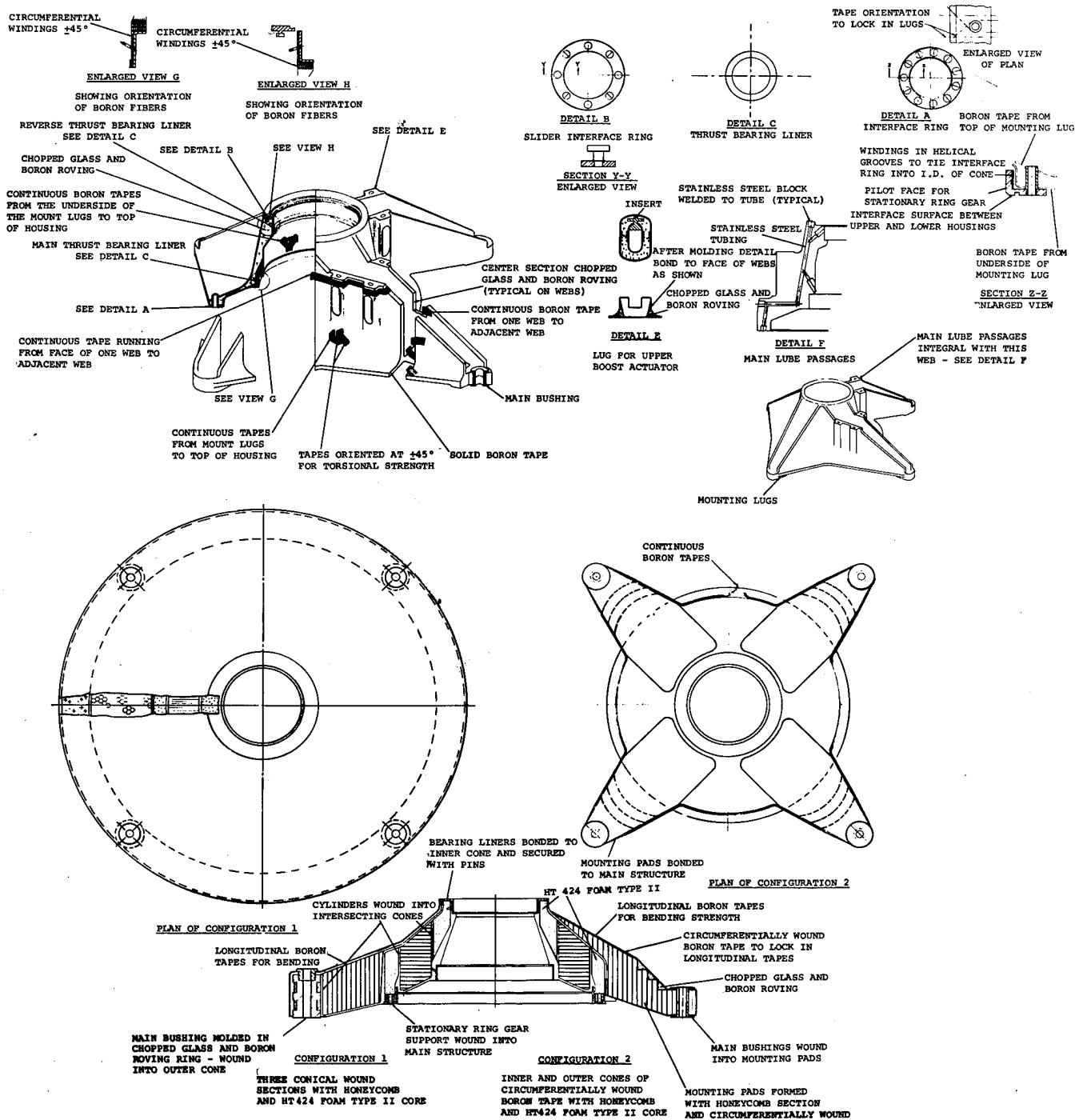


FIGURE 12. BORON COMPOSITE APPLICATIONS TO FORWARD TRANSMISSION UPPER COVER

nated the need for 4 intermediate shaft support points in the CH-47:

The drive shaft design study (Figure 13) features a tube which has honeycomb-reinforced walls and molded plastic end fittings with boron surface reinforcing for bending strength. The

splined adapters are steel and are wound into the basic tube section. Configuration I shown in Figure 13 is the basic design for application to existing aircraft. The weight saving per aircraft from boron applications to the drive shafting is 52 percent for the CH-46 and 47 percent for the CH-47.

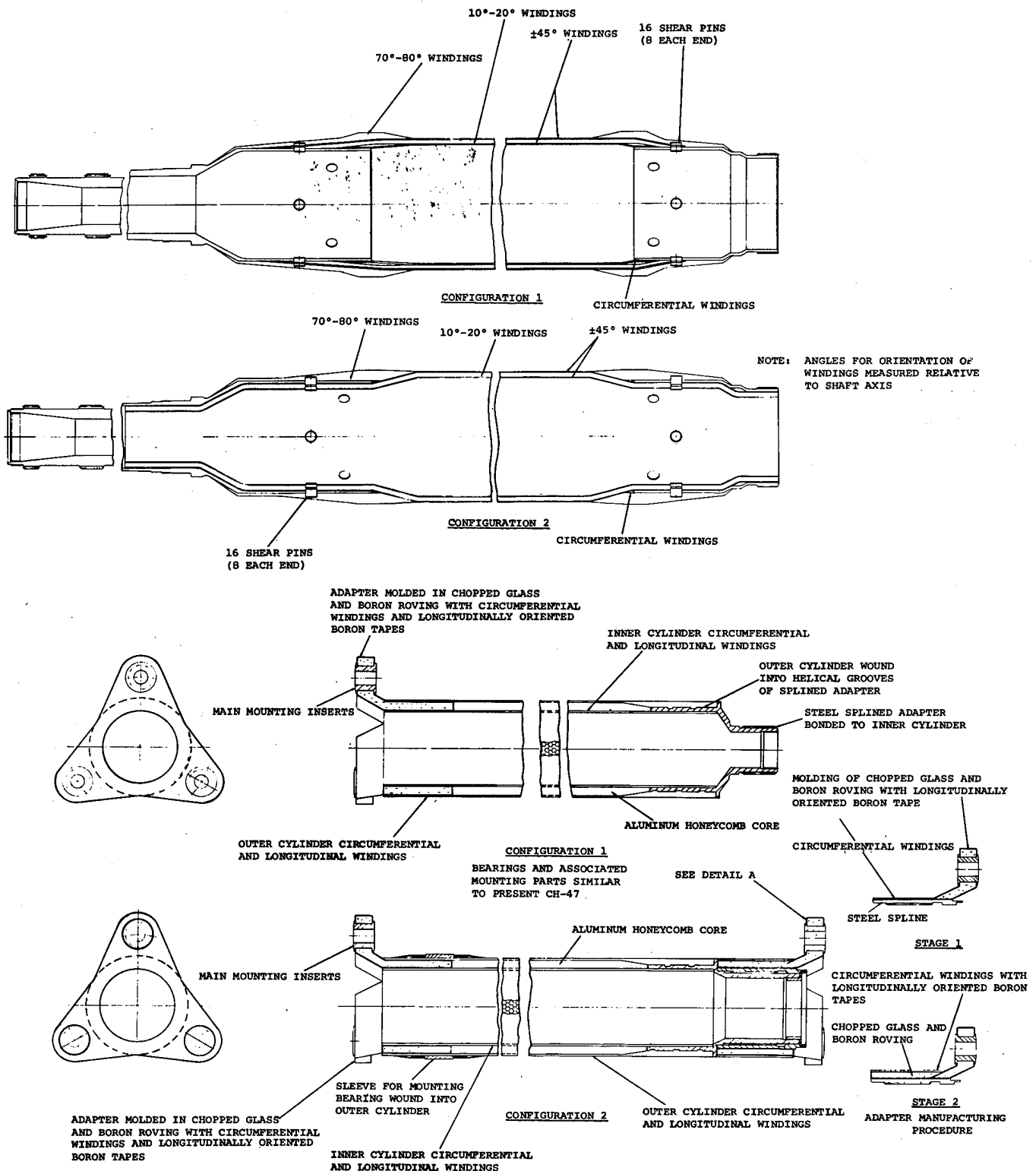


FIGURE 13. BORON COMPOSITE APPLICATIONS TO AFT ROTOR SHAFT AND SYNCHRONIZING SHAFT

The aft rotor drive shaft with extension (shown in Figure 13) is a straightforward application of boron composite to achieve both a weight saving and a stiffness improvement. Both application objectives are obtained, with an additional improvement in the ease of manufacture.

Two design configurations are shown in Figure 13; Configuration I is the basic design study item, which allows the extension tube to be formed by a continuous filament-winding process that completely entraps the two steel end fittings. The design eliminates the shrink-fit assembly operation normally employed to assemble the present aluminum shaft extension. A 41-percent improvement in shaft flexural stiffness (seen as rotation stiffness at the upper lift bearing) is also obtained in this design.

The relationship of the upper lift bearing life versus shaft slope angle indicates that, as the minimum shaft slope on the curve is approached, the improvement in bearing life is 20 percent of current life per degree of change in slope; therefore, the boron application provides an improvement in current bearing life. A 39-percent weight saving has been calculated for this item.

The airframe study was limited to the basic load-carrying elements which are shown in Figure 14. The scope of the program did not allow for an extensive study of composite replacement structures for the shear elements, but the literature indicates that flat-sheet advanced composites with stability characteristics equivalent to aluminum are also equivalent in weight per square inch. Therefore, the study centered on the payoff associated with the replacement of the beam cap and web stiffening elements. A method of indexing these elements was developed to account for the necessary column and crippling stability characteristics in the weight-estimating procedure. A sinusoidal or bead-shaped element was selected as the replacement element for use in the study. This approach resulted in an indicated weight saving of 38 percent in the basic structural weight of the CH-46 and CH-47.

A summary of the impact on structural system weight from the application of boron advanced composites is shown in Table I. The items summarized are those which satisfy both a reasonable design execution and an integrity evaluation.

The definition of the composite application to the rotor blade required a more detailed study approach since the results were to establish the baseline configuration of the preliminary design blade. The initial study evaluated the relative merits of several rotor blade cross sections similar to those shown in Figure 15. The objective was to select the configuration which provided the best range of stiffness potential at a minimum weight. Figure 15 shows the results of the evaluation, with the C-spar identified as the optimum section. On the basis of rotor weight trend data and a preliminary rotor mean coning angle criterion, a 275-pound rotor blade was established as the baseline for the parametric study outlined in Figure 16. The objective was to take full advantage of the capability to distribute both mass and stiffness in the blade design through the use of composites. The approach taken is shown in Figure 16; the principle variables of mass and composite modulus were varied over a practical range. The resultant effects were developed in the form of carpet plots for centrifugal force, static deflection, coning angle, blade frequencies, and so forth.

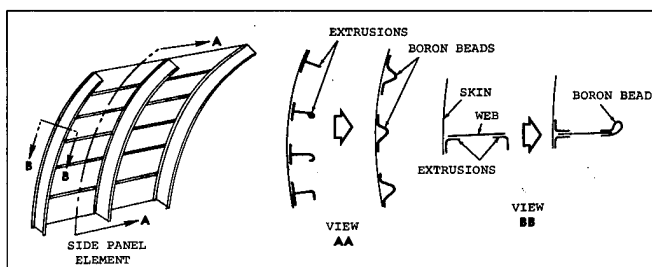
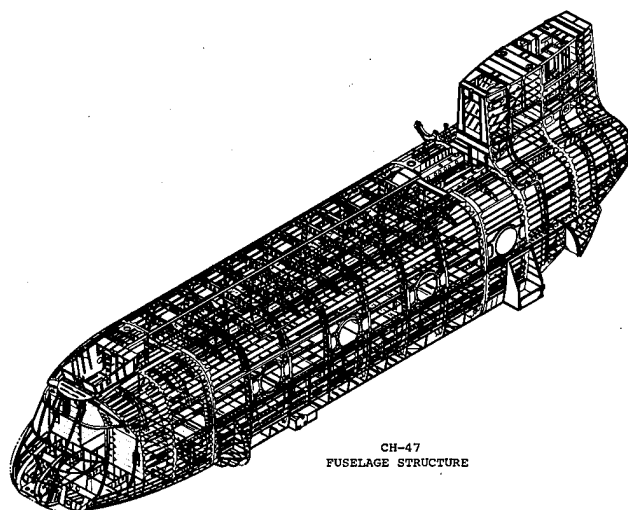


FIGURE 14. BORON COMPOSITE APPLICATIONS TO CH-47 FUSELAGE STRUCTURE

The final phase of the effort is to mark out the areas on the carpet plots which violate the predetermined design criteria. The open regions on each plot are then crossplotted on some single meaningful plot, such as the first flapwise natural frequency, to determine if a design window exists for the baseline blade weight being studied. A typical result of this technique is shown in Figure 17, which shows a surprisingly small design window; however, this should not be interpreted as a fundamental limitation. Once the basic window is established it can be altered by taking advantage of the ability to modify the fiber orientation or volume content of the composite, or by reevaluating the target blade weight, or by a combination of all three. Naturally, a modification of the initial criteria may be in order as the characteristics of the blade become known.

Conclusion

In summation, the first 9 months of effort have established a technical base for the application of advanced composites to helicopters, have shown that there are technical payoffs in many areas, and have provided the structural information for determining the cost and operations effectiveness. Initial efforts on the rotor blade have indicated that the anticipated advantages of composites can be achieved. However, they have also revealed that there is much to be learned about the application of these unique materials before the maximum payoff can be achieved.

CH-47	Nomenclature	Basic Material	Basic Weight Pounds	Boron Composite		CH-46	Nomenclature	Basic Material	Basic Weight Pounds	Boron Composite	
				New Weight						New Weight	
				(F _{TU} -KSI)						(F _{TU} -KSI)	
				102	200					102	200
			Pounds	Pounds				Pounds	Pounds		
<u>Rotor Group</u>											
	Rotor hub	steel	231.2	209.0	177.0		Hollow horizontal pin	steel	75.1	87.7	87.7
	Drive arm	aluminum	9.4	6.4	6.4		Rotary wing hub	steel	99.6	90.14	76.6
	Lower drive arm	aluminum	2.4	1.6	1.6		Drive scissors arm	aluminum	4.5	3.0	3.0
	Rotating ring assembly	aluminum	91.8	96.0	96.0		Swashplate upper ring	aluminum	33.7	35.4	35.4
	Swashplate ring assembly	aluminum	75.1	79.0	79.0		Lower swashplate	aluminum	34.8	36.8	36.8
	Subtotal		409.9	392.0	360.0		Subtotal		247.7	253.0	239.5
	Δ Weight	-	-	-17.9	-49.9		Δ Weight	-	-	+5.3	-8.2
	% Change	-	-	-4.4	-12.2		% Change	-	-	+2.0	-3.3
<u>Drive System Transmissions</u>											
	Support assembly	magnesium	8.9	9.4	8.25		Aft rotor center shaft	aluminum	58.0	59.1	35.46
	Forward transmission support	aluminum	143.9	113.9	99.0		Forward upper case	aluminum	92.0	72.8	63.7
	Forward housing	magnesium	53.5	56.0	44.0		Rotor brake support	magnesium	6.4	6.7	5.3
	Housing assembly	magnesium	44.8	46.9	41.0		Forward lower case	magnesium	42.2	44.1	38.6
	Housing assembly	magnesium	54.3	56.8	49.6		Mix box case	magnesium	22.4	23.4	20.5
	Transmission bevel gear support assembly	magnesium	8.0	8.4	7.0		Aft upper case	magnesium	25.8	26.9	23.5
	Engine drive shaft assembly	aluminum	8.9	6.9	5.9		Pinion adapter	magnesium	4.9	5.2	4.5
	Lift bearing housing	aluminum	33.9	26.9	22.7		Aft transmission housing	magnesium	52.7	55.1	48.7
	Aft rotor shaft	aluminum	75.6	77.0	46.1		Subtotal		304.4	293.3	240.3
	Subtotal		431.8	402.2	324.6		Δ Weight	-	-	-11.1	-64.1
	Δ Weight	-	-	-29.6	-107.2		% Change	-	-	-3.6	-21.1
	% Change	-	-	-6.8	-24.8						
<u>Drive System Shafting</u>											
	Synchronizing shaft assembly	aluminum-steel	46.2	43.4	36.9		Blower tube assembly	aluminum	1.4	1.1	1.0
	Shaft subassembly	aluminum-steel	26.2				Shaft assembly	aluminum-steel	24.5	26.1	22.2
	Synchronizing shaft assembly	aluminum-steel	23.1	17.9	15.2		Shaft assembly	aluminum-steel	25.1		
	Shaft subassembly	aluminum-steel	11.0				Shaft assembly	aluminum-steel	25.1	26.2	22.3
	Synchronizing shaft assembly	aluminum-steel	20.0				Shaft assembly	aluminum-steel	18.9		
	Shaft subassembly	aluminum-steel	8.9	13.8	11.8		Subtotal		95.0	53.3	45.5
	Fan drive shaft assembly	aluminum	1.9	1.5	1.3		Δ Weight	-	-	-41.7	-49.5
	Subtotal		137.7	76.6	65.2		% Change	-	-	-43.8	-52.1
	Δ Weight	-	-	-61.1	-72.5						
	% Change	-	-	-44.4	-52.6						
<u>Airframe</u>											
	Structure assembly	aluminum	1766.7	1251.0	1081.0		Cockpit fuselage structure assembly	aluminum	985.4	701.0	607.0
	Δ Weight	-	-	-515.7	-685.7		Δ Weight	-	-	-284.4	-378.4
	% Change	-	-	-29.1	-38.8		% Change	-	-	-28.9	-38.4

TABLE 1. WEIGHT SAVINGS FROM BORON APPLICATIONS

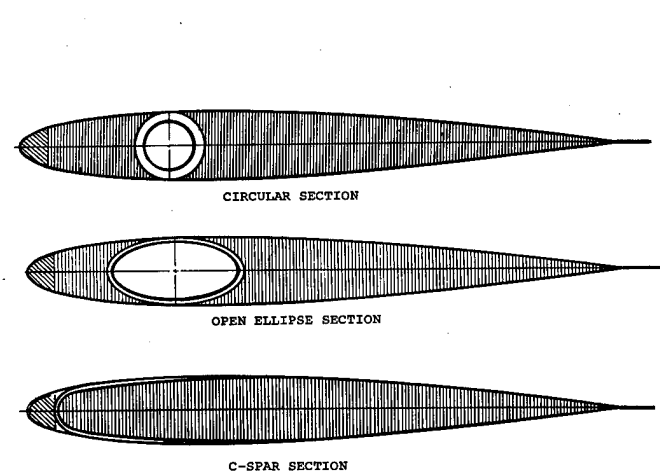


FIGURE 15. BLADE CROSS SECTION STIFFNESS COMPARISON AT CONSTANT WEIGHT

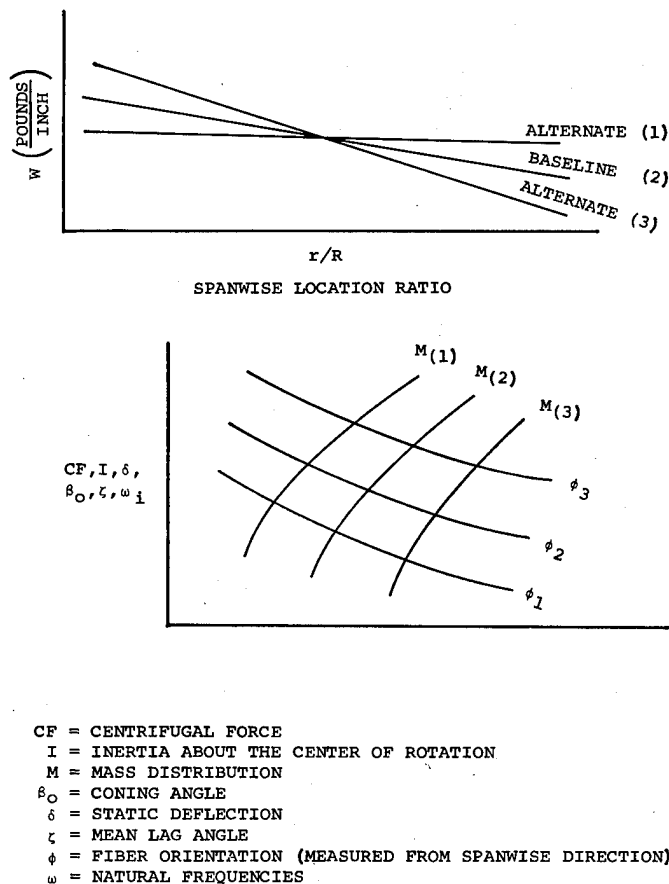


FIGURE 16. CARPET PLOTS SHOWING EFFECT OF M AND ϕ ON OTHER DESIGN PARAMETERS

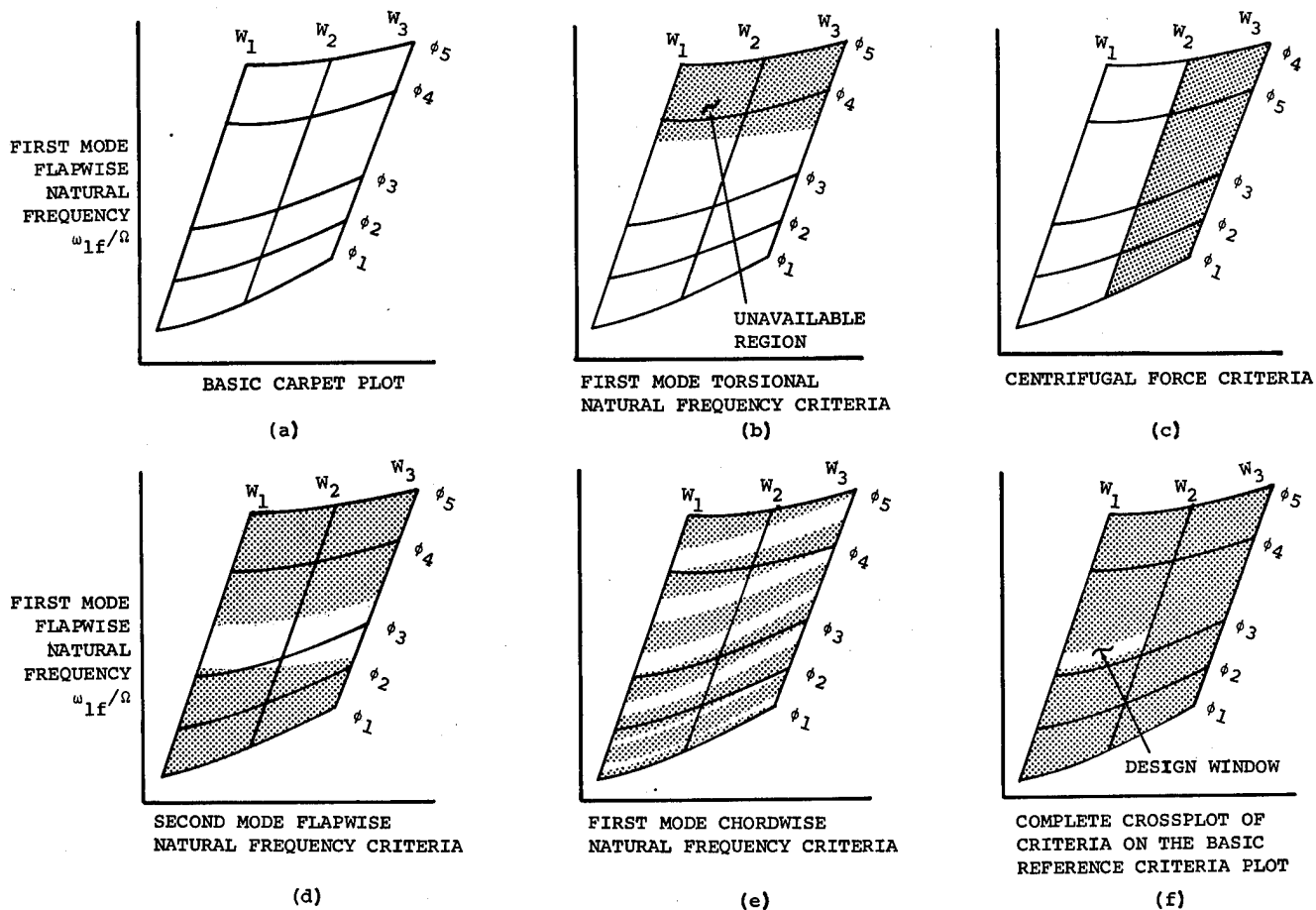


FIGURE 17. CROSSPLOT OF DYNAMIC PROPERTIES AND DESIGN CRITERIA

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- 1) Research and Development of Helicopter Rotor Blades Utilizing Advanced Composite Materials, First Quarterly Report, Boeing Document D8-0471-1, September 1966.
- 2) Research and Development of Helicopter Rotor Blades Utilizing Advanced Composite Materials, Second Quarterly Report, Boeing Document D8-0471-2, December 1966.
- 3) Research and Development of Helicopter Rotor Blades Utilizing Advanced Composite Materials, Third Quarterly Report, Boeing Document D8-0471-3, March 1967.